超磁歪材と圧電材を用いた磁気力制御方法とその応用に関する研究

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論文内容要旨

1. INTRODUCTION

We propose new magnetic force control method using giant magnetostrictive materials (GMM). This magnetic force control is based on the large inverse magnetostrictive effect of GMM and can be realized by a composite device of GMM and piezoelectric actuator (PZT). Since PZT actuator has high electrical resistance, this saves much energy and generates no heat in static operation. In this paper, magnetic levitation system with the composite device is proposed and the advantages of the low power consumption and low heat generation were examined in experiments.

2. MAGNETIC FORCE CONTROL METHOD USING GIANT MAGNETOSTRICTIVE MATERIAL

Ferromagnetic material deforms in magnetic field, while the magnetization in the material varies with applied stress. The former phenomenon is called magnetostrictive effect and the latter is inverse magnetostrictive effect. Magnetostriction of Fe and Ni are in the order of 10 ppm at the largest, but "giant magnetostrictive material" known as Terfenol-D has more than 2000 ppm of magnetostriction. Since its discovery, many applications utilizing this large strain and force have been proposed in actuators and sensors. Another advantage of giant magnetostrictive material is that since it interacts with magnetic circuits by its magnetization, its variation caused by stress can be transduced into different kind of variation such as magnetic force.

Figure 1 illustrates a magnetic circuit that converts variation of stress into that of magnetic force. The magnetic circuit consists of mainly two parallel magnetic circuits, one, labeled with 1, consisting of a permanent magnet and the gap between the yokes, and other labeled with 2, composed of the magnet and the GMM rod. The magnet provide steady-state attractive force between yokes and induce a bias magnetization in the rod. According to inverse magnetostrictive effect, the magnetization of the rod (equal to flux in circuit 2) varies with stress in the rod, and therefore the magnetic force can be adjusted by controlling the stress. For example, when compressive stress is applied to the rod, flux in circuit 2 decreases, and conversely magnetic force increase. Using this method, a constant force can be maintained by a constant stress. Terfenol-D is suitable for this kind of application, because under proper pre-stress and bias magnetic field, it provides low stiffness, low relative permeability and high piezomagnetic constant.

Figure 2 shows the schematic of the experimental arrangement to demonstrate the principle. The magnetic circuit was constructed from a Terfenol-D rod, a Nd-B-Fe magnet (D16L30, D: Diameter, L: Length) and fixed and movable yokes (gap area:20×15mm^2), and set to the lower cross-head of a universal test machine. Compressive stress up to 30MPa was applied to the rod by a steel piston fixed on the upper cross-head. The attractive force exerted on the movable yoke was measured by a load cell(200N) and the strain was measured by strain gages attached to the rod. Four cases with different size of rods (D10L10, D10L20, D14L10, D14L20) were investigated at every 0.2mm fixed gap (0.2 to 2.0mm).

Figure 3 and 4 show stress - strain and strain - force curve in the case of gap=0.2mm. It can be seen that the proper attractive force was generated at stress of 0MPa and was increased as the compressive stress was applied. For example, with the rod of D14L10, the force was increased from 23N to 53N when the strain was raised for 0 to 1050ppm in the case of gap=0.2mm. While stress - strain curve is quite non-liner and has large hysteresis due to the ΔE effect of magnetostrictive materials that the stiffness changes with applied magnetic field and stress, the strain-force relation is almost linear and has small hysteresis. Therefore we

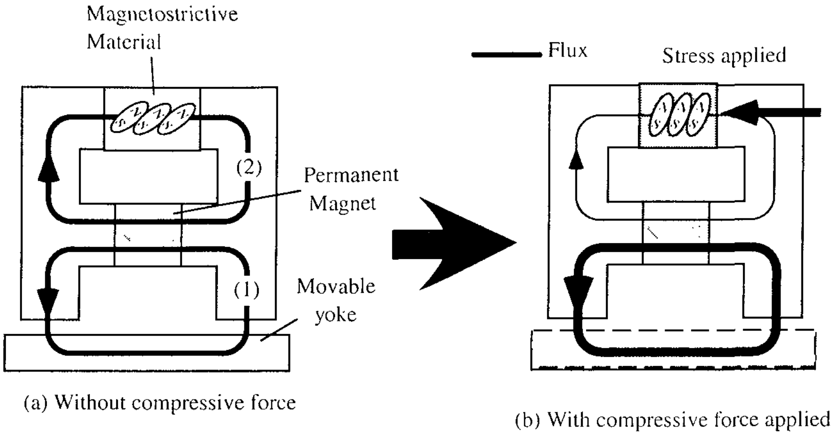

Figure 1. Magnetic circuit wit magnetostrictive material

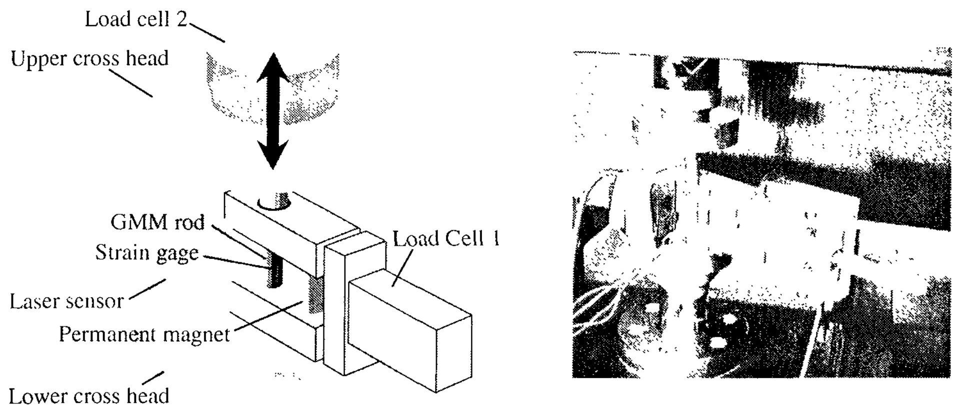

Figure 2. Experimental setup

introduced variation ratio of force K_{fs} with strain ($= F_w/S_w$ as shown in Fig.4) and examined behavior of K_{fs} that depends on components of the magnetic circuit. K_{fs} can be derived by solving an equivalent magnetic circuit as follow.

$$K_{fs} = -\frac{A_m \; B_g|_{S_m}}{\mu_o} \frac{P_g}{P_g + P_l + P_p} \times \partial B_m / \partial S_m|_{H_m} \tag{1}$$

where, P_g, P_p, P_l are permeances of gap, magnet and leakage, and A_m is area of the rod. B_0 is bias flux density in the gap at 0 stress and can be calculated by FEM analysis considering B-H characteristics of Terfenol-D at 0 stress. $\partial B_m/\partial S_m|_{H_m}$ is a material property of Terfenol and must be measured in experiments. As Fig.5 shows, theoretical calculations were in agreement with experimental results and it was confirmed that K_{fs} is dependant upon (proportional to) the cross-sectional area, but not the length of the rod.

Energy transformation ratio η was defined as U_o/U_i, where U_o is change of magnetic energy in the gap and U_i is work done to deform the rod in a cycle of loading and unloading. The ratio η was calculated for different cases and maximum η of 0.54 was obtained in the case of the rod D14L10, the magnet D22L30 and fixed gap of 0.4mm. To increase η, the change of stiffness must be considered in magnetic circuit design and this can be achieved by referring material properties of Terfenol-D in the solution of equivalent magnetic circuit.

3. MAGNETO-ELECTRIC ELEMENT FOR MAGNETIC FORCE CONTROL

The most advantage of the proposed magnetic force control method is that the force can be adjusted by applying stress. For example, by putting weight on the rod, the force can be kept without any energy and heat generation. To make full use of this advantage, we must control the stress with devices which need little energy to keep the stress, therefore we propose an magneto-electric(ME) element which is a composition of GMM and a piezoelectric actuator. In the element, stress of the GMM rod is controlled by the voltage

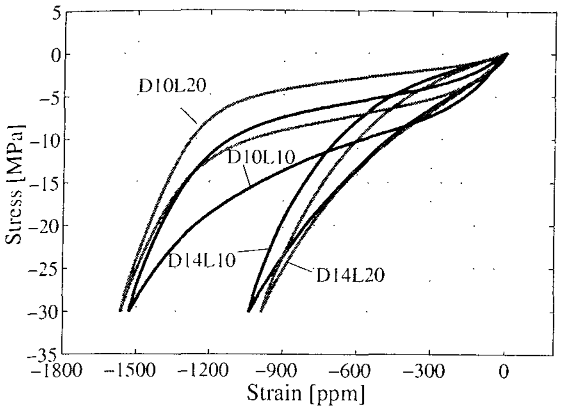

Figure 3. Strain - stress(Gap:0.2mm)

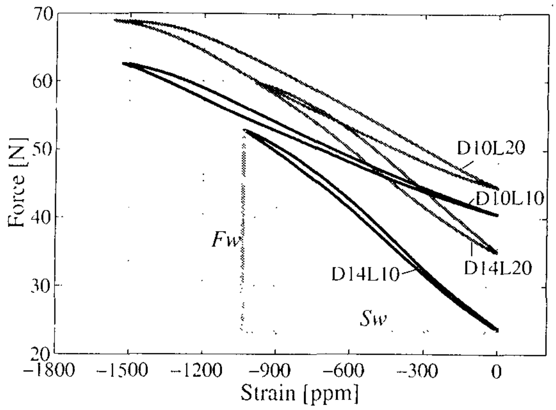

Figure 4. Strain - force(Gap:0.2mm)

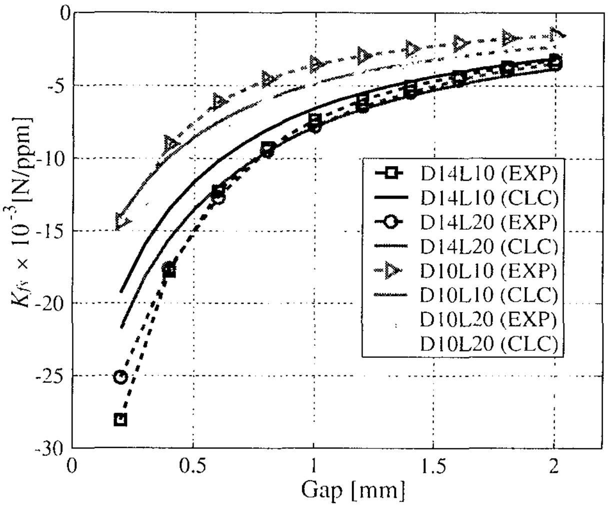

Figure 5. Comparison of K_{fs}

of the actuator, so that by composing closed magnetic circuits with an outer movable yoke, the magnetic force can be controlled by voltage. The piezoelectric actuator is suitable because it generates large force sufficient to deform the GMM rod and moreover it requires little energy in static operation. In addition to it, the response of the actuator is high (in μsec order) enough to change the strain, so that this element is applicable to systems which need high response.

Figure 6(left) shows the compositions of the ME element. The ME element consists of yoke 1, GMM rod, yoke 2, a stack piezoelectric(PZT) actuator and yoke 3 and they all are lined up and compressed by bolts. The stress applied on the rod can be controlled by input voltage applied to the actuator. For example, when the voltage is increased, compressive stress on the rod is increased. Since permanent magnets are inserted between yoke 1 and 2, two parallel magnetic circuits, one consisting of magnet and GMM rod 1 and the other consisting of magnet and gap 2, are composed with a movable yoke. The permanent magnets provide steady-state attractive force between the yokes and induce a bias magnetization in the rod. Since the variation of magnetization caused by the variation of stress in the rod is furthermore converted to the variation of magnetic force in this parallel magnetic circuit, the attractive force can be controlled by the voltage.

The ME element is composed of a stack PZT actuator (TOKIN: AE101016, area:11×11mm^2, length:16mm) that generates 3500N of blocked force and free displacement of 16μm at 150V and a Terfenol-D rod (diameter:12mm, length:9mm) and four Nd-B-Fe magnets(area:6×6mm^2, length:9mm). The gap area of both the yoke 1 and yoke 2 are 32mm×12mm. The compression by 4 bolts provides appropriate prestress on both the rod and actuator.

Figure 7 shows the ME element and an experimental apparatus used to measure attractive force acting on the movable yoke. The strain of the rod was measured with 4 strain gages wired in series so as to give average signal. Constant and sinusoidal voltage generated by a signal generator was amplified through a

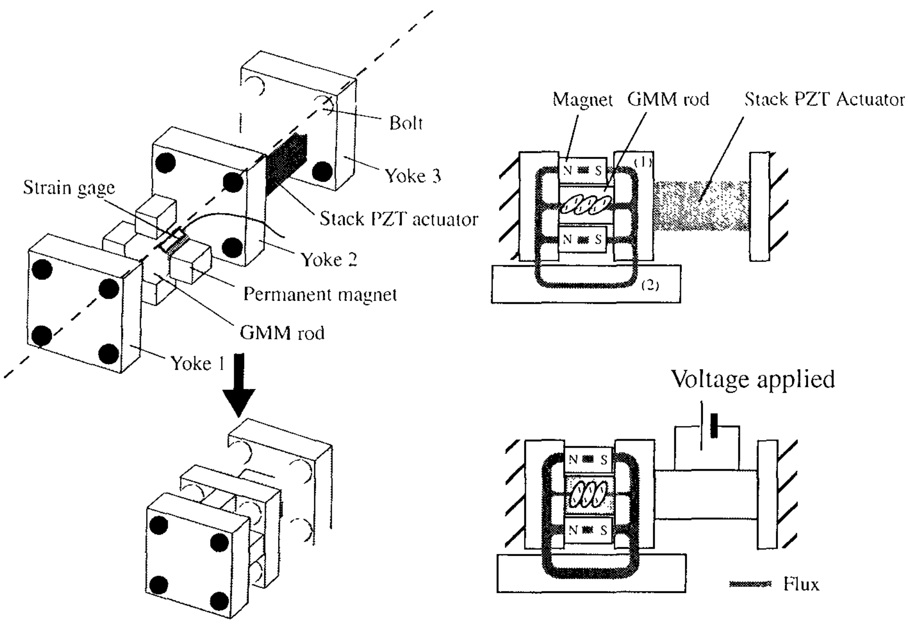

Figure 6. Composition of ME element(left) and force control with ME element(right)

voltage amplifier and applied to the PZT actuator. Static attractive force was measured with a load cell. In high frequency range, it is impossible to measure the small variation of the force because of the restrictions in the resolution and bandwidth of the load cell. Thus the flux variation in the gap was measured by a pickup coil wound around the yoke 2. The flux variation in the rod was also measured by a pickup coil wound around it.

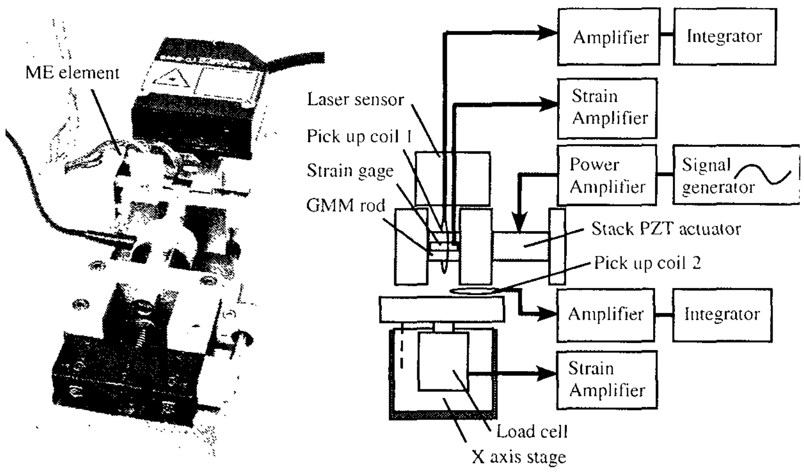

Figure 7. Measurement setup

Figure 8 shows measured relationship between the voltage, strain, force and current taken at constant gap of 0.2mm with sinusoidal voltage (amplitude:pp150V, offset 75V,1Hz) applied. The mechanism of force control described above was confirmed by the result that the force increased with the voltage, from 19N(0V) to 23N(150V), and the strain decreased from 0(0V) to -350ppm(150V). A hysteretic relationship between the voltage and force, which is inherited from the actuator and the magnetostrictive rod, was observed. The ME element required current of 5mA to get maximum force variation.

Figure 9 shows the frequency response of the strain and the magnetic flux density taken by application of random noise up to 20kHz. The bandwidth of flux in gap was about 2kHz. Generally magnetization can respond to strain with little delay even in high frequency range, so that the difference of phase between the strain and the flux density is due to eddy current occurred in the yoke.

The advantages of this element compared with electromagnets are summarized as follows.

- Energy consumption is very low at low driving frequency and almost zero in static operation. Electromagnets need current supply to generate constant force even in steady state.
- Heat generation is small in low frequency and almost zero in static operation. Electromagnets generate Joule heat in coil.
- In electromagnets, mainly the inductance of coils dominate the response of current, however this element has no coil and the response depends on the performance of the actuator used to change the strain of GMM rod.

The performance of the element is mainly dependent on piezoelectric actuator.

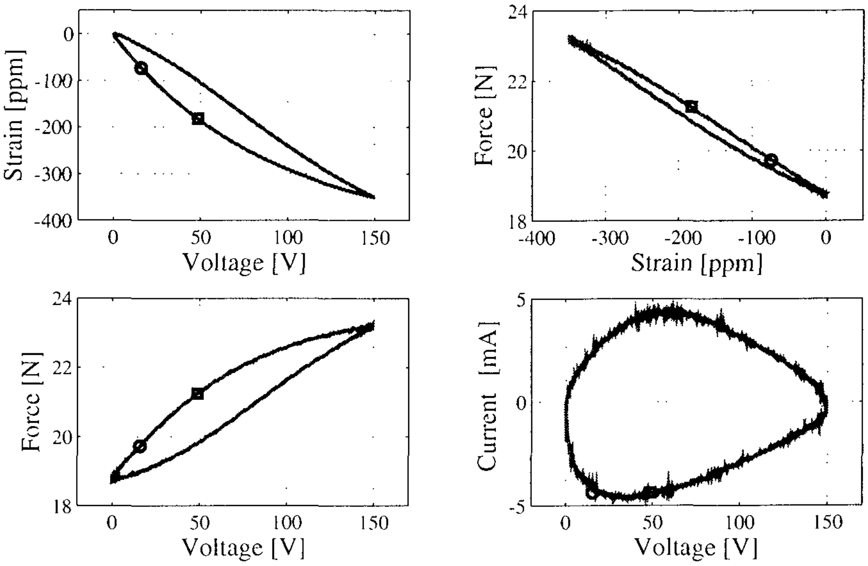

Figure 8. Voltage, strain, force and current (Gap=0.2mm)

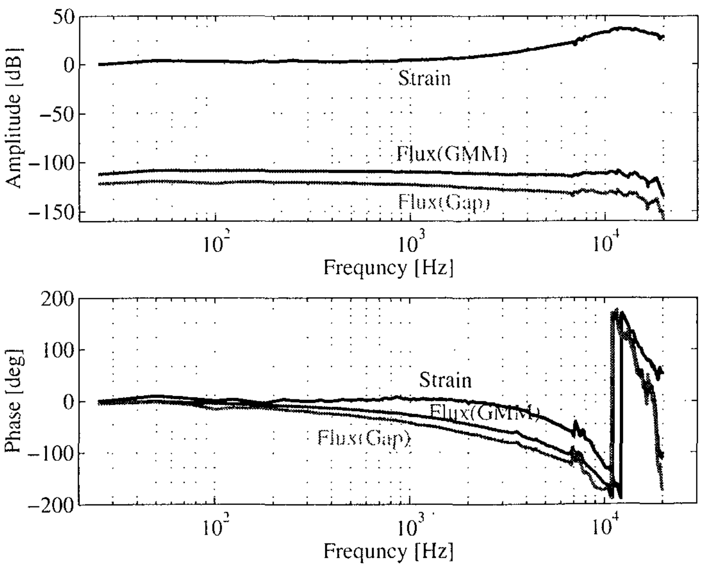

Figure 9. Frequnecy responce of strain and flux (Magnitude(up), Phase(down))

4. MAGNETIC LEVITATION SYSTEMS WITH ME ELEMENT

We proposed magnetic leviation systems with ME elements. In conventional levitation system using electromagnets, current must be continuously supplied to sustain constant levitation force and this causes heat generation and energy loss. To save energy, zero power system is proposed in which permanent magnets are used in conjunction with electromagnets. The levitation system with the ME element has the same advantages of the zero power system, however it is superior in the point that energy consumption and heat generation become zero at any position of the levitated yoke. We demonstrated this advantage by an experimental setup shown in Fig.10. Here input voltage is controlled so as to balance the attractive force with the gravity acting on the levitated yoke (movable yoke).

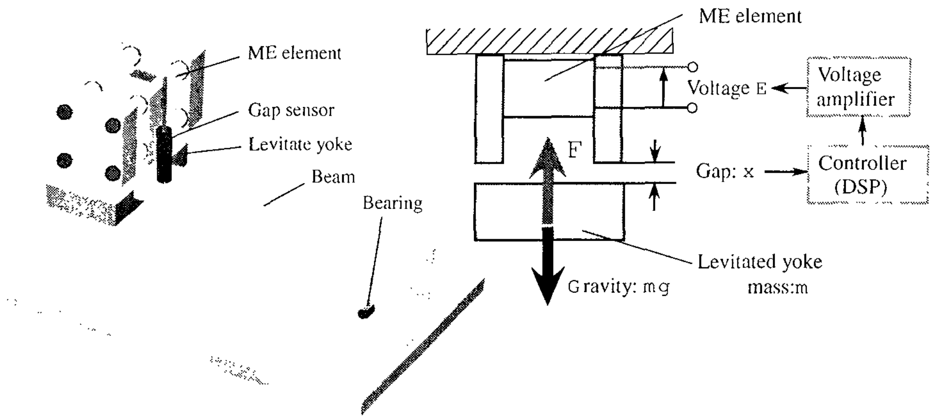

Figure 10. Levitation system with ME element

The attractive force F is a function of gap X and voltage E. Assuming that the bias attractive force F_0 is equal to the gravity in operation point P, F can be linearized and kinetic equation of the yoke around P is written in the form of Eq.(2) considering small variation (e,x) of (E,X) from P.

$$m\ddot{x} = mg - F_0 - \left.\frac{\partial F}{\partial X}\right|_{E_0,X_0} x - \left.\frac{\partial F}{\partial E}\right|_{E_0,X_0} e \tag{2}$$

$$m\ddot{x} + K_X x + K_E e = 0 \tag{3}$$

Here

$$K_X = \left.\frac{\partial F}{\partial X}\right|_{E_0,X_0}, K_E = \left.\frac{\partial F}{\partial E}\right|_{E_0,X_0} \tag{4}$$

The motion of yoke is unstable because K_x is negative in Eq.(3). By applying PD control so that input e is a linear combination of x and $\dot{x}$:

$$e = k_p x + k_d \dot{x} \quad (k_p, k_d > 0) \tag{5}$$

where k_p and k_d are gains of PD controller. Substitution of Eq.(5) into Eq.(2) gives

$$m\ddot{x} + k_d K_E \dot{x} + (K_X + k_p K_E)\, x = 0 \tag{6}$$

This system is stable if

$$K_X + k_p K_E > 0 \tag{7}$$

In order to design the gain k_p and k_d, we simply obtained K_X and K_E from the slope of X versus F curve measured at constant voltage of 0V and E versus F curve measured at constant gap of 0.8mm. Figure.11 show the input voltage and the attractive force controlled around P in which k_p is set to 600, 1200 and 1800 V/mm. The input voltage is calculated by a DSP using sensed signal of the gap. When k_p is more than 600V/mm, the inclination of the curve changes from negative to positive and the motion of yoke is stable. It is desirable to set larger k_p to stabilize the motion, but larger k_p makes the range of stabilizalbe gap narrower because of the limitation of input voltage.

Around operation point P, the yoke vibrated for short time and finally became stable. Figure 12 shows step responses of the displacement, input voltage and current. From these results, it can be seen that current was kept zero in steady state, even the position of the yoke and voltage was shifted, These results supported the advantage of this system of low power consumption and low heat generation. Even this system includes non-linearity and hysteresis, it can be modeled as same as that with electromagnets. Therefore the element can be easily installed in a conventional magnetic levitation system.

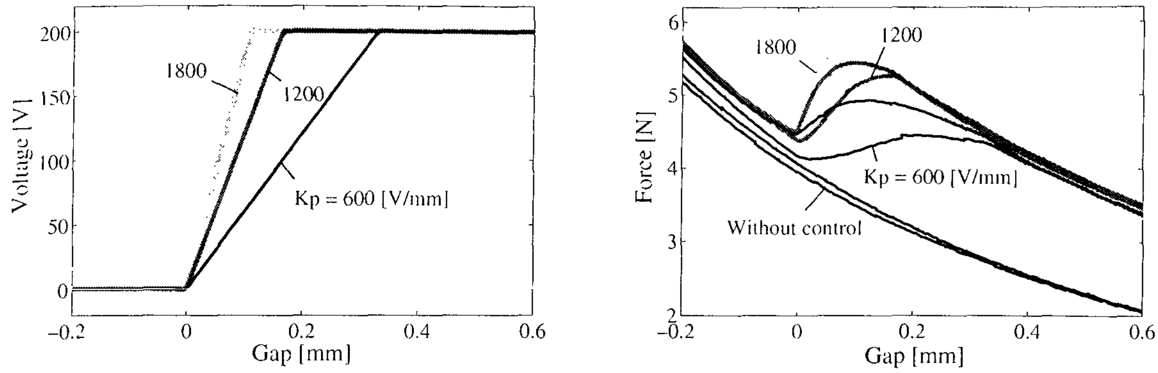

Figure 11. Controlled voltage (left) and force (right)

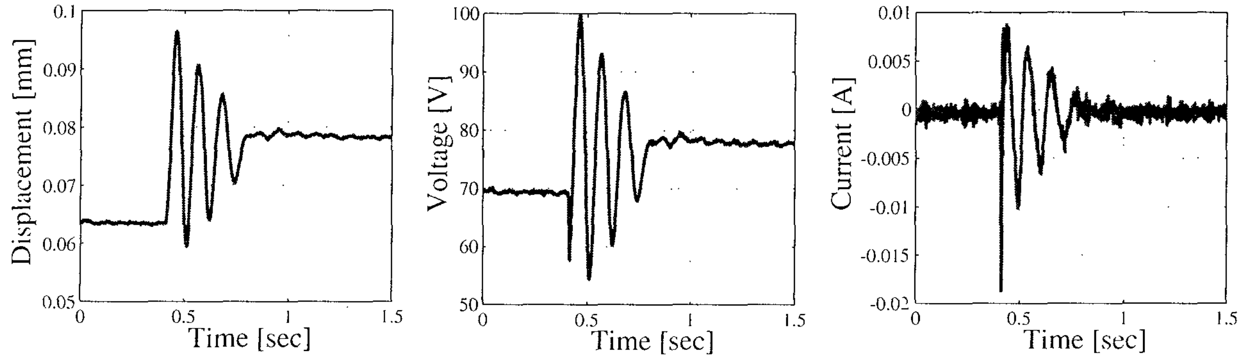

Figure 12. Step response of displacement voltage and current

5. CONCLUSION

In this paper, we proposed magnetic force control method by inverse magnetostrictive effect and developed a composite element (ME element) of two functional materials: giant magnetostrictive material and piezoelectric material. After the investigation of the static and dynamic behavior of attractive force and magnetic flux, it was confirmed that the element can control the magnetic force by voltage and has wide bandwidth compared with electromagnets. As an application of the element a magnetic levitation system using the element is proposed and it is confirmed to have the advantage of low energy consumption and heat generation.

審査結果の要旨

電磁力を制御する電磁機器は，一般に電磁石を用い，その励磁電流を制御するが，コイルの発熱が，その実用の制限となる場合が少なくない．また定常の制御では，電流供給のための，電力消費が問題になる．そのため，本研究では超磁歪材料で電磁力を制御する方法を提案し，これを圧電材料との複合化で実現し，電磁力制御に付随する発熱と電力消費の低減化を目指した．本論文は，この磁気力制御法の基礎原理，その実現法，そして応用を含めた有用な研究成果をまとめたもので，全編5章からなる．

第1章は序論である．

第2章では，磁性材料の逆磁歪効果を用いた応力による磁気力の制御法を提案した．これは，磁歪材料の負荷応力による磁化の変化を，磁気回路により吸引力の変化に変換する方法で，定常時の電力消費，発熱が零になる特長を有する．この原理を実験で実証し，超磁歪材料がこの方法に適した磁歪材料であることを確認した．また磁気回路の形状に依存する吸引力の変化を等価磁気回路法により導出した．これらは，工学的に有用な知見である．

第3章では，超磁歪材料と圧電材料を複合化した電磁変換素子を提案し，第2章で述べた磁気力制御方法を実現した．このため，超磁歪ロッドと積層型圧電アクチュエータを機械的に複合した並列と直列型の2種類の素子を製作した．並列型の素子では，電圧で吸引力を制御する原理を実証し，吸引力の変化が増加するように形状の設計を行った．またより汎用性のある直列型の素子を製作し，同様に電圧で吸引力を制御できる原理を実証した．更に吸引力の動特性の測定を行い，これが高周波域においても，よく応答することを確認した．これらは重要な成果である．

第4章では，電磁変換素子を磁気浮上技術に応用した．素子による簡単な浮上制御実験を行い，実用レベルでの電磁力の制御が可能であること，また素子のもつ低発熱，低電力消費の特徴がシステムに反映されることを確認した．また推進力を制御する素子を提案，試作し，これが電磁アクチュエータに応用可能であること示した．これらは実用上有益な知見である．

第5章は結論である．

以上要するに本論文は，超磁歪材料を用いたコイルレスな電磁力の制御方法を提案し，これを実現する方法，並びにその電磁変換素子の設計方法を明らかにしたものであり，機械電子工学の発展に寄与するところが少なくない．

よって，本論文は博士（工学）の学位論文として合格と認める．